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COMMENTS

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Transition towards carbon-neutral electrical systems for China: Challenges and perspectives

Keywords carbon neutrality, power systems, electrification, renewable energy

1 Ambitious goal towards carbon-neutral power systems in China

International Panel on Climate Change (IPCC) revealed the necessity to neutralize CO_2 emissions from global energy systems by mid-century in order to contain the temperature raise below 1.5°C by 2100. China, accounting for over 30% of global CO_2 emissions, represents the largest challenge globally for decarbonization. In September 2020, at the 75th United Nations General Assembly (UNGA), President Xi announced that China will strive to peak carbon emissions by 2030 and to achieve carbon neutrality by 2060. Following the commitment, policies have been advanced to achieve these goals. The government announced a target for over 12 billion kW of wind and solar installation by 2030, ramping up the cumulative investment level 3 times in a decade, leading to a 65% reduction in the CO_2 emission intensity relative to the level in 2005.

The energy structure in China has been changing rapidly since the new Millennium. The installed capacity of China's wind and solar power increased hundredfold within a decade since the establishment of the renewable energy law in China in 2005, reaching 535 GW in 2020 (data source: *China Electric Power Statistics Yearbook 2021*). The regional developments of both wind and solar power are indicated in Fig. 1. Such a large scale development is mainly attributed to the rapid decline of levelized cost from renewable power. The levelized cost for solar photovoltaic (PV) decreased by 77% between 2010 and 2018 (IRENA, 2019a). The total installed cost of electricity for onshore wind droped over half since 2010 (IRENA, 2019b). Both wind and solar power have reached the grid parity (Tu et al., 2019; 2020), indicating that the per-unit generating cost for wind and solar power is lower than that of thermal generators for different regions globally. Wind and solar power are becoming even more competitive given the rapid rise of coal and natural gas price recently.

Going into the future, the Chinese government is committed to achieving 1200 GW of renewable power by 2030. In order to realize carbon neutrality by 2060, the cumulative renewable investment level is expected to reach 4200 to 5800 GW (Energy Research Institute, 2015; He et al., 2016; Chen et al., 2021) . Such a radical transformation from China's current carbon-intensive energy system will require an investment of over one hundred trillion yuan. Definition of the optimal investment portfolio for different renewable energy technologies, geographical distribution for the investments, deployments of storage systems, opportunities for transportation electrification and hydrogen production are all essential considerations for an economical and secure transition in the power systems. Significant challenges exist in the power systems to realize such a transition.

2 Key challenges going forward

Grid integration of renewable energy. Integrating the intrinsically variable renewable power generation into the current inflexible generation mix in China represents the primary challenge. Over 15 billion USD of economic loss has been incurred due to wind curtailment between 2010

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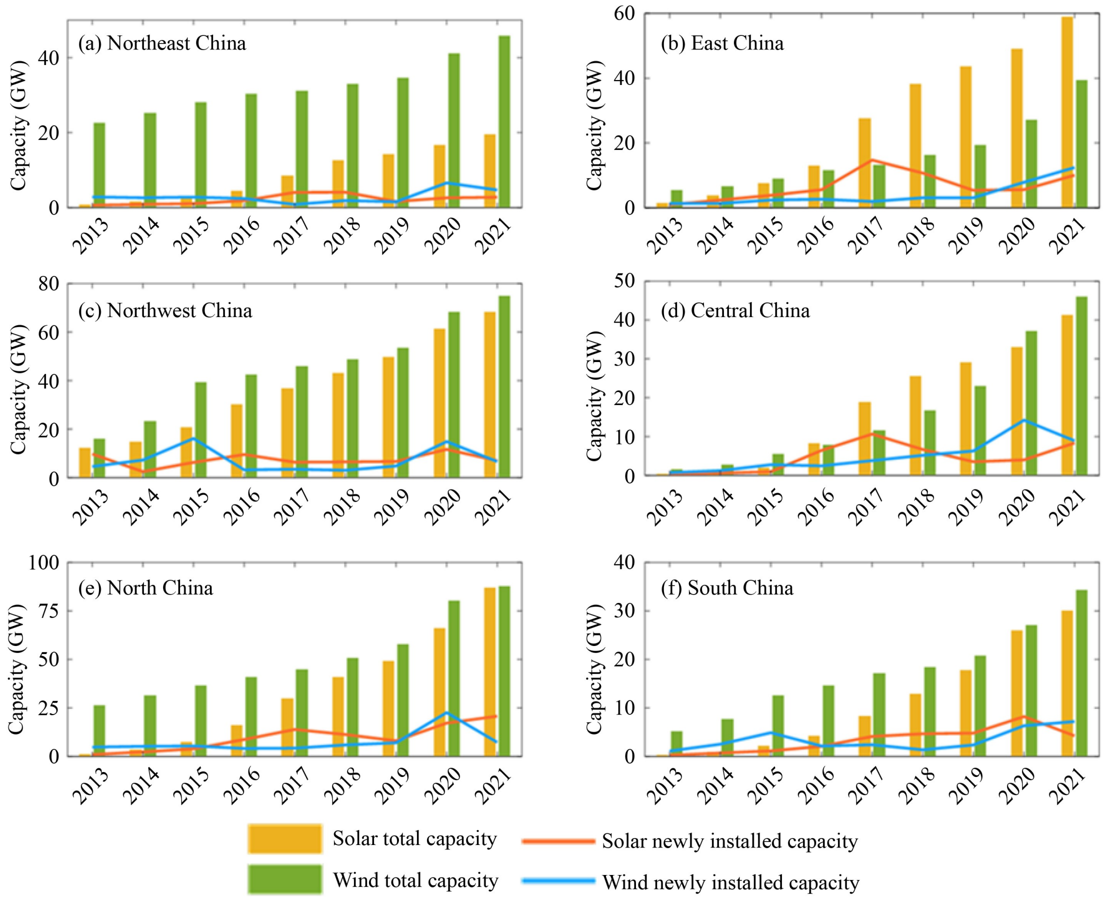

Fig. 1 The regional distribution of wind and solar investments in China.

and 2019 (Qi et al., 2018; NEA, 2020a), when renewable investment level was lower than 28 GW (NEA, 2020b). China's National Reform and Development Commission and National Energy Administration (NEA) have jointly suspended the approval of wind project when curtailment rate is higher than certain level. Going forward, the renewable penetration will increase at least 10 times to achieve carbon neutrality, and accommodation of variable renewables on such a scale will be critical to realize the transition.

Maintaining reliable energy supply. More than 10 provinces, including Guangdong and Zhejiang, faced power supply shortages in 2021. During the power shortage in Northeastern China, the wind power capacity factor dropped to about 5% of the rated level. On the other hand, approval of coal-fired power plants has been slowing in China. The newly installed thermal capacity equals only half of the increase in peak power demand between 2019 and 2021. The extreme weather condition has led to rapid increase in peak power consumption attributed to air-conditioning and tightening the approval of fossil-fuel power plants raised the concern about the sufficiency of power supply. How to maintain a reliable power supply with a continuous increase in the penetration of variable renewables poses a central challenge during the transition.

Facilitating the large-scale electrification. The transition towards a carbon-neutral energy system assumes significant electrification in the final energy consumption. The electrification rates of light-duty vehicles are expected to reach 77% by 2050 in China (An et al., 2019). The stock of light-duty electric vehicles (EVs) will reach 380 million across China, imposing additional electricity consumption of 2 trillion kWh. Accommodating these EVs will double the anticipated national power demand if the charging power is poorly managed, and will incur potentially formidable additional investments in the power sector infrastructure. However, the electrification strategy and pathway as well as the proper management scheme of EV charging are still unclear due to the lack of integrated model which could capture the operational interaction between power systems and electrified transportation.

3 Analytical framework

Facing these challenges, a comprehensive analytical framework extending the conventional power system planning model is required. Chen et al. (2021) introduced a cross-sector, high-resolution assessment model to design the pathway towards carbon neutrality for China's power and energy systems, as shown in Fig. 2. The assessment model incorporated renewable resource analyses, hourly simulation of power system operations, charging schedules for electrified transportation and optimal investment in power system infrastructure. High-resolution meteorological, geographical and bathymetric data are applied to assess the provincial potential and hourly variations of onshore/offshore and solar energy. An integrated expansion model is proposed to determine the installed capacities, the distribution of investments in renewable energy, the interprovincial transmission network, storage systems, and Power-to-Gas (P2G) technologies. To capture the obstacles posed by the operational inflexibility of thermal units, hourly simulation of 31 provincial power systems for a full year is embedded in the aforementioned investment model. Employing the unit-level operational parameters of 5500 fossil-fuel power plants, all flexibility constraints (ramping, minimum up/down times, minimal output, and reserve) are formulated for every unit to fully describe the flexibility issue. A fast unit commitment model is introduced to accelerate the process of solving the investment planning problem. For transmission expansion, all possible interprovincial connections with different voltage levels for alternating/direct current (AC and DC) transmission types are considered. Then the scale of potential connections is reduced based on a newly proposed pre-optimization model to make it feasible to solve the investment planning problem. For different strategies of electrified transportation (fast and slow), statistics on driving behaviors (arrival times, departure times, and the state of charge) are incorporated in the Monte Carlo simulation to generate provincial charging demand profiles. For storage and P2G system, the technical and economic characteristics of promising technologies (pumped hydro and lithium batteries for storage; alkaline electrolysis, polymer-electrolyte membrane electrolysis, as well as solid-oxide electrolyzer for P2G) are applied in the study.

Based on the analytical framework, over 60 scenarios are simulated and optimized in Chen et al. (2021), allowing for different penetrations of renewables, various flexibility modeling representations, different levelized cost projections for renewables, storage, and coal prices, as well as the electrification assumptions for EVs and power-to-hydrogen. Results show that the diverse variation of amortized capital cost and annual operation cost could be as high as 2.3 trillion yuan among different decarbonization pathways. The optimized low-carbon transition pathway in Chen et al. (2021) is not only feasible but also less expensive than alternative fossil-fuel based power systems. Compared to a province-based transition roadmap, the proposed nationwide transition strategy will reduce the total annual cost by 1.2 trillion yuan, equivalent to 2/3 of the annual public health expenditure in China. When reaching 80% of renewable penetration in 2050, the optimization model indicates that at least 1700 GW of onshore wind power, 1350 GW of solar power and

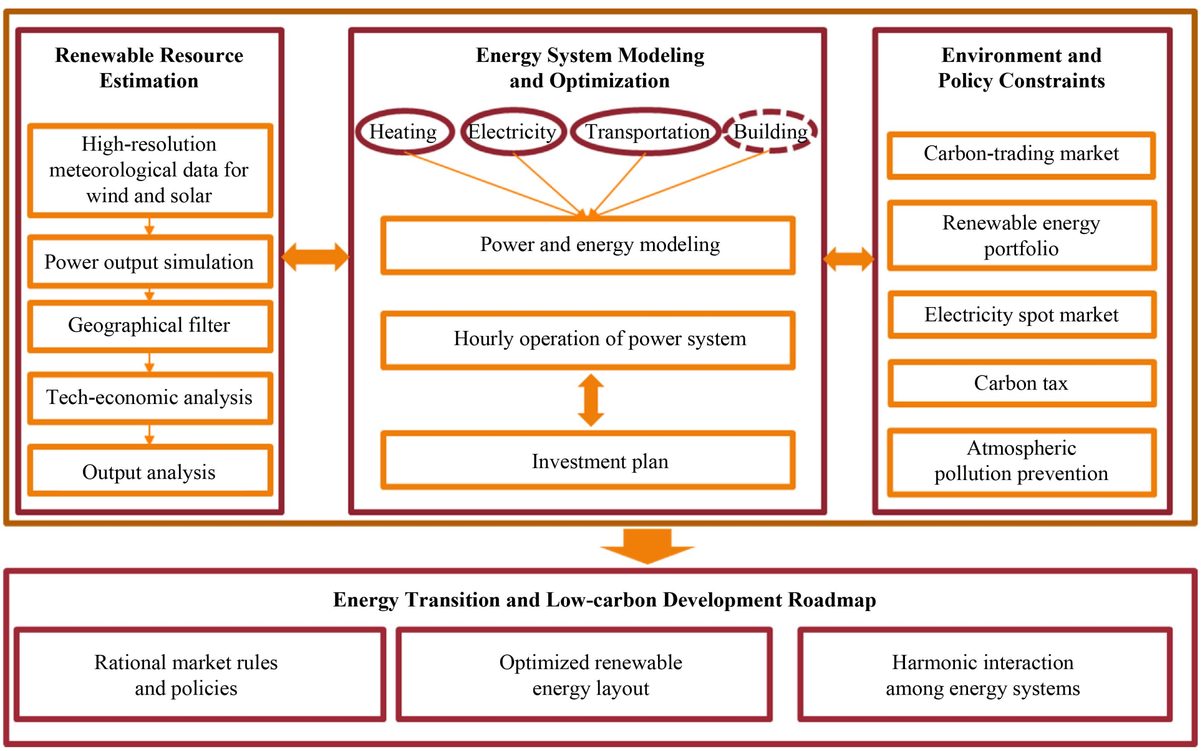

Fig. 2 Modeling structure for energy system optimization (adapted from Chen et al. (2021)).

900 GW of offshore wind power are required, supplemented with 350 GW of energy storage. 89% of onshore installed capacity will be located in "three north" area (Northwest, Northeast, and North China) which is featured with superior wind conditions. The installed solar capacity in 2050 is mainly distributed over Northwest, North and East China because of the abundant solar resources. Offshore wind, which is close to China's economic centers, will be the crucial building block to decarbonize the costal power systems. Critical factors contributing to the cost-effective transition are discussed in the following section.

4 Critical factors for the economical and reliable energy transition

Harnessing the hydro flexibility to synergize the renewable power. China obsesses a unique opportunity to confront the challenge of the variability of renewables compared with the United States and the European Union (Qi et al., 2018). The installed hydropower capacity of 390 GW in China (data source: *China Electric Power Yearbook 2018*) could potentially provide a freely available regulation ability of 8160 GWh on a daily basis for power systems, equivalent to 600 million Tesla Power Walls. Exploiting the flexibility of hydropower to facilitate the accommodation of renewable electricity could avoid the expenditure of 600 billion USD on storage. More importantly, hydro flexibility could tackle the variation of renewables beyond the daily cycle, effectively complementing the time scale for battery technologies. However, the current pricing structure is not encouraging this synchronization. Integrated system planning and comprehensive pricing structure reform for hydro power are required to facilitate the grid integration of variable renewable energy and to reduce curtailments at elevated renewable penetration levels.

The expansion of ultra-high voltage (UHV) transmission network. The geographical imbalance between renewable energy resources and electricity demand hinders the integration of renewable electricity. Over 80% of onshore wind capacity is installed in Northern China (NEA, 2020a), and 80% of China's hydropower potential is sited in the western region (Liu et al., 2016), while 70% of total national electricity consumption is concentrated in the eastern or coastal region (data source: *China Electric Power Yearbook 2018*). However, current decarbonization targets are allocated on a provincial basis, and thus the renewable investment plans are decided at the provincial level in the "14th Five-year Plan". Results in Chen et al. (2021) have illustrated that a coordinated transition plan at a national level could reduce the CO_2 abatement cost by 63% compared with an optimized plan for deployment implemented at a provincial level. Large scale expansion of transmission network not only improves the power supply reliability, but also mitigates variability of renewable energy through larger balancing zones. The major benefits of significant expansion of ultra-high transmission lines are attributed to the reduction of energy storage costs, the optimized geographical allocation of wind and solar investments and reduced wind and solar curtailment rates. National level coordination of decarbonization plans are strongly recommended in the research.

Optimization of charging strategies for electric vehicles. As mentioned above, China will have a stock of over 380 million EVs, which will require more than 2 trillion kWh of electricity every year. The choice of charging mode for such a large scale EV fleet will have a significant impact on the operation of power systems. Chen et al. (2021) quantified the interaction between the power system and the electrified transportation sector considering different charging strategies. Results show that different options of the charging strategy for EV fleet could result in differences in investment of over 800 billion yuan. Smart charging management will also provide the regulating ability to the power system. The expansion of slow-charging facilities at workplace should be prioritized in the pathway to carbon neutrality of China's energy system, to better synchronize the availability of excessive solar power at noon.

Significant opportunities for power-to-hydrogen technologies. The hydrogen alliance in China predicts that the national demand for hydrogen in 2050 will reach approximately 34 million and 24 million tons for industry and for the transport sectors, respectively. The hydrogen production industry, if powered by fossil fuel, would emit 750 million tons of CO_2. Production of hydrogen by electricity could contribute not only to the accommodation of renewable electricity but also to CO_2 mitigation, with the auxiliary benefit of providing additional operational flexibility for power systems. Chen et al. (2021) indicates that deployment of P2G equipment under an 80% renewable penetration scenario would reduce the CO_2 abatement cost to below zero. Special attention should be paid to the application of P2G technologies with potentially significant wind curtailment in such provinces as Inner Mongolia and Xinjiang.

5 Conclusions

Chinese government has highlighted the target of achieving carbon neutrality and implemented a series of policies since 2020. This paper offers insight into the challenges faced by power systems, introduces a novel analytical framework for the transition of China's electrical energy systems, and defines several critical factors to which researchers and policymakers need to pay attention. Given the current situation of significant economic loss associated with renewable curtailment as well as restrictions in electricity policy in over ten provinces, the integration of large amounts of renewable energy and reliable and secure electrical energy supplies pose primary obstacles for the transition of China's power systems. In addition, the electrification of other sectors, for example the transportation sector, will introduce additional electricity demand to power systems. How to appropriately manage the power generation and transmission to fulfill the additional electricity need is another important problem in the background of the carbon neutrality transition. Chen et al. (2021) proposed an analytical framework and an integrated investment model to address the above-mentioned problems in designing a feasible and profitable pathway towards carbon neutrality. The researchers refined four important critical factors for the future development of China's power systems based on the simulation results: 1) hydro stations with large reservoirs can provide operational flexibility for power systems and large energy storage potential and could significantly synergize the accommodation of renewable energy; 2) the expansion of UHV transmission lines could reduce the annual expenditure for China's power systems by 1.2 trillion yuan; 3) employing P2G technologies could not only facilitate the accommodation of renewable energy but also improve the economic efficiency; and 4) the slow-charging strategies for EV will provide extra operational flexibility and make the carbon neutrality transition more economical. These factors should be highlighted in discussions of ongoing national infrastructure expansion projects.

References

An F, Kang L P, Qin L Z, Mao S Y, Wang W W, Ben Dror M (2019). A Study on China's Timetable for Phasing-Out Traditional ICE-Vehicles. China Oil Consumption Cap Plan and Policy Research Project. Beijing: Innovation Center for Energy and Transportation (iCET) (in Chinese)

Chen X Y, Liu Y X, Wang Q, Lv J J, Wen J Y, Chen X, Kang C Q, Cheng S J, McElroy M B (2021). Pathway toward carbon-neutral electrical systems in China by mid-century with negative CO_2 abatement costs informed by high-resolution modeling. Joule, 5(10): 2715–2741

Energy Research Institute (2015). China 2050 High Renewable Energy Penetration Scenario and Roadmap Study. Beijing: Energy Research Institute, National Development and Reform Commission of China

He G, Avrin A P, Nelson J H, Johnston J, Mileva A, Tian J W, Kammen D M (2016). SWITCH-China: A system approach to decarbonizing China's power system. Environmental Science & Technology, 50(11): 5467–5473

International Renewable Energy Agency (IRENA) (2019a). Future of solar photovoltaic

IRENA (2019b). Power generation costs

Liu X C, Tang Q H, Voisin N, Cui H J (2016). Projected impacts of climate change on hydropower potential in China. Hydrology and Earth System Sciences, 20(8): 3343–3359

NEA (2020a). Grid connected operation of wind power in 2019 (in Chinese)

NEA (2020b). Wind power grid operation in the first quarter of 2020 (in Chinese)

Qi Y, Dong W J, Dong C G, Huang C W (2018). Fixing Wind Curtailment with Electric Power System Reform in China. China's Energy in Transition Series. Beijing: Brookings-Tsinghua Center for Public Policy

Tu Q, Betz R, Mo J L, Fan Y, Liu Y (2019). Achieving grid parity of wind power in China: Present levelized cost of electricity and future evolution. Applied Energy, 250: 1053–1064

Tu Q, Mo J L, Betz R, Cui L B, Fan Y, Liu Y (2020). Achieving grid parity of solar PV power in China: The role of Tradable Green Certificate. Energy Policy, 144: 111681